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A New Method for Electromagnetic Time Reversal in a Complex Environment *

KONG Qi(孔旗)[1], SHI Qing-Fan(史庆藩)[1]**, YU Guang-Ze(于广泽)[1], ZHANG Mei(张梅)[2]**

[1]*School of Physics, Beijing Institute of Technology, Beijing 100081*

[2]*School of Computer, Guangdong Industrial University, Guangzhou 510006*

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A new time reversal method is proposed to infer the location of an unknown extending target in a complex environment. In our method, the wavelet analysis and scalogram of energy density are first introduced into the electromagnetic time reversal process to improve the accuracy and to eliminate noises. The computation results show that the new technique can refocus the unknown target better than using traditional time reversal.

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Time reversal (TR) techniques can realize detection and localization of unknown targets by using the invariance wave equation.[1] The experimental implementation of TR is now well established in both acoustics and electromagnetics.[2–8] Although the scattering of unknown targets has been studied extensively, it is worth mentioning that traditional TR methods have limitations in complex environment and weak scattering. For example, the noise has an adverse impact on the time reversal detection.[9] It is this open problem that inspires us to solve this disadvantage. In this Letter, we develop a new TR technique which combines the wavelet analysis and the scalogram of energy density (SED) to improve the accuracy and eliminate noise. In this new SED method, a transmitter is firstly settled in the inhomogeneous medium. It emits a TM incident wave to the area containing an infinitely extending target. The scattered TM waves that contain the target information are received by an antenna array. Secondly, the received scattering waves are processed to obtain the SED signals. This step is able to translate the received electromagnetic fields into scalar energy scalograms so that the scattering waves are powerfully amplified. The SED method is utilized as a match filter in the noise scenario. Due to the adaptive time-frequency localization property of wavelet transform, a better resolution is provided in both the time domain and the frequency domain. Thirdly, the processed signals are time reversed, and then re-radiated through the same medium for target locating. By visualizing the field response during a simulation, wave propagation can be observed directly on a computer screen. Numerical results show that the present method is robust and more tolerant to a complex medium than the traditional TR methods.

Hereby, we consider a model as depicted in Fig. 1. An unknown extending target is situated at $\boldsymbol{r}'$ in a time-invariant complex field, and a receiver array A is located at $\boldsymbol{r}_p$. The array probes the complex medium that is of infinite extent. The transmitter is settled at $\boldsymbol{r}_s$ and may be an electric or a magnetic line source. Here we confine our discussion to the TM case, $p(t)$ is the time domain pulse emitted from transmitter S, which is described as

$$p(t) = e^{-t^2/2}\cos(5t). \tag{1}$$

Based on the electromagnetic theory, the fields incident at $\boldsymbol{r}'$ due to the source are written as

$$\begin{aligned} E^{\rm inc}(\boldsymbol{r}', t) &= p(t)^* G(\boldsymbol{r}', \boldsymbol{r}_s, t) \\ &= \int p(\tau) G(\boldsymbol{r}', \boldsymbol{r}_s, t-\tau) d\tau, \end{aligned} \tag{2}$$

where $G(\boldsymbol{r}', \boldsymbol{r}_s, t-\tau)$ is Green's function in free space,[10] $*$ represents temporal convolution, assumed for notational simplicity as scalar (two-dimensional) fields and Green's functions. Extension of the vector case is straightforward in principle, but is complicated to express in a general form. Theoretically, the scattering waves from the target are just viewed as perturbations so that we can neglect the multiple scattering according to the Born approximation.[11] Thus, the total field at the $k^{\rm th}$ receiver can be expressed as

$$\begin{aligned} E^{\rm tot}(\boldsymbol{r}_k, t) &= E^{\rm inc}(\boldsymbol{r}_k, t) \\ &\quad + \int G(\boldsymbol{r}_k, \boldsymbol{r}', t)^* E^{\rm inc}(\boldsymbol{r}', t) o(\boldsymbol{r}') d\boldsymbol{r}', \end{aligned} \tag{3}$$

where $o(\boldsymbol{r}')$ is a function that represents the conversion of excitation fields $E^{\rm inc}(\boldsymbol{r}', t)$ into equivalent currents that re-radiate as secondary sources (constituting scattered fields).[12] Based on the above formula, the scattering field observed at the $k^{\rm th}$ receiver is

$$\begin{aligned} E^{\rm sca}(\boldsymbol{r}_k, t) &= E^{\rm tot}(\boldsymbol{r}_k, t) - E^{\rm inc}(\boldsymbol{r}_k, t) \\ &= \int G(\boldsymbol{r}_k, \boldsymbol{r}', t)^* E^{\rm inc}(\boldsymbol{r}', t) o(\boldsymbol{r}') d\boldsymbol{r}'. \end{aligned} \tag{4}$$

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**To whom correspondence should be addressed. Email: qfshi123@bit.edu.cn; zm8828@126.com

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In traditional TR methods, $E^{sca}(\boldsymbol{r}_k, t)$ is directly applied to reverse the target. However, there is a significant impact on the detection performance if the target is in a complex electromagnetic environment.[9] In fact, there is a more efficient way to reconstruct the target in the complex medium. We define the electric part of electromagnetic energy density as

$$w_E = \frac{1}{2}\varepsilon E^2. \tag{5}$$

Furthermore, the SED method accompanied with a wavelet transform is introduced to process w_E. The optimal extraction of useful signals can be picked up by using the mother wavelet $(\psi(t))$ to match the energy density. Note that the wave shape of $(\psi(t))$ is chosen as the Morlet wavelet that equals to the source $p(t)$ in wavelet analysis. The wavelet sequence acquired through the mother wavelet is written as

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\Big(\frac{t-b}{a}\Big), \tag{6}$$

where a and b are the dilation and translation factors, respectively. Then the continuous wavelet coefficient $WT_w(a,b)$ obtained by convolving the signal w_E with the wavelet sequence is given as

$$WT_w(a,b) = |a|^{-\frac{1}{2}} \int_{-\infty}^{+\infty} w_E \cdot \psi\Big(\frac{t-b}{a}\Big)dt. \tag{7}$$

The wavelet coefficient indicates the correlation between the scattering signal and the mother wavelet. When the scattering signal is mostly related to the mother wavelet in time domain, the wavelet coefficient will reach the maximum value.

According to the scalogram theory,[13] we define the SED expression in the electromagnetic field as

$$\mathrm{SED}(a,b) = \frac{100|WT_w(a,b)|^2}{\int |WT_w(a,b)|^2 db}. \tag{8}$$

The SED process can shift the geometric center of time domain window to the energy center of an unknown target. Hence, after the processing, SED signals have a much better time-frequency concentration and less interference. Thus, the optimal extraction of the scattering signal will be achieved by using the SED method as a matched filter, and the background noises can be effectively removed.

Based on the SED method presented, numerical calculation is carried out by the two-dimensional finite-difference time-domain (FDTD) algorithm that guarantees the correctness of simulation.[14] The dimension of the electromagnetic field is divided into $2\lambda \times 2\lambda$ grids. Clutter randomly settles around the unknown target to simulate the complex environment. A TM incident wave centered at 0.1 GHz is emitted from the transmitter at $(x, y) = (1\lambda, 0.2\lambda)$. The unknown target is located at $(x, y) = (1.2\lambda, 0.6\lambda)$ with radius $R = \lambda/50$ and relative permittivity $\varepsilon_r = 10$.

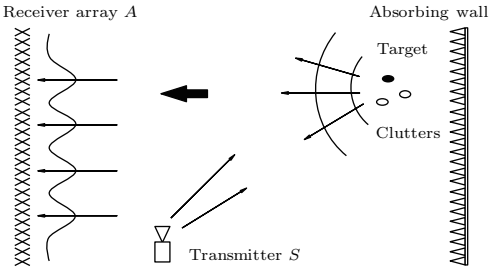


Fig. 1. Schematic diagram of the time reversal process.

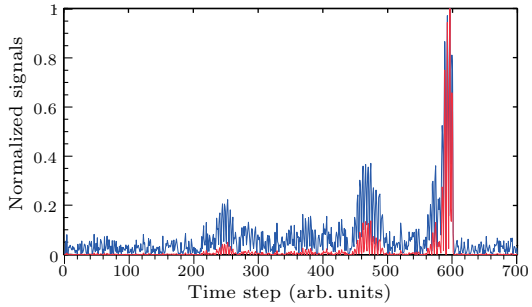


Fig. 2. Comparison of unprocessed- and SED-signal in a noise-free scenario.

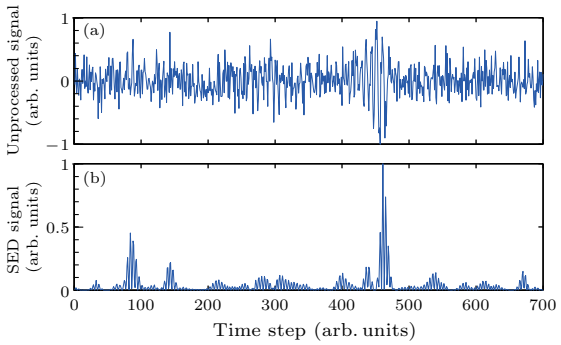


Fig. 3. (a) Unprocessed signal and (b) SED signal in noise scenario (SNR = −12 dB).

The emitted TM incident is scattered and received by the antennas whether the target exists or does not exist. The scattering waves are first processed by the continuous wavelet analysis and then translated into SED signals. Subsequently, SED signals are time reversed and propagate backward into the complex medium for locating the target.

In order to clarify the SED method vividly, an example of the unprocessed signal received by the 18th antenna is depicted by the absolute value in Fig. 2. Obviously, the SED process can reduce signals generated by the random clutters.

In a noise scenario, the unprocessed signal received by the 7th antenna is shown in Fig. 3(a). Useful information from the target submerged in the noise can be effectively extracted by using the SED method (see Fig. 3(b)).

Consequentially, the imagings in the noise-free scenario with the traditional method and the SED method are shown in Figs. 4(a) and 4(b). It is clear that focusing by the SED method is more accurate than that using the traditional method. In the noise scenario, the traditional method cannot detect the target (see Fig. 5(a)) while the SED method can give a better performance (see Fig. 5(b)). Therefore, the SED method can successfully focus the location of the target with higher resolution.

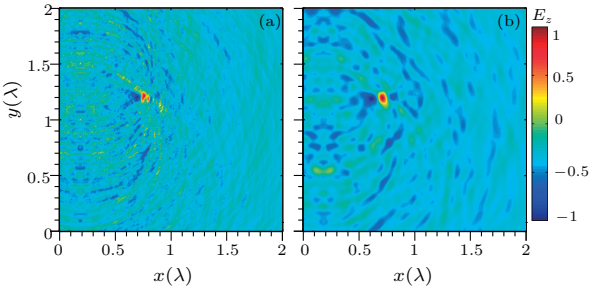


Fig. 4. Imaging results by (a) the traditional TR method and (b) the SED method in a noise-free scenario.

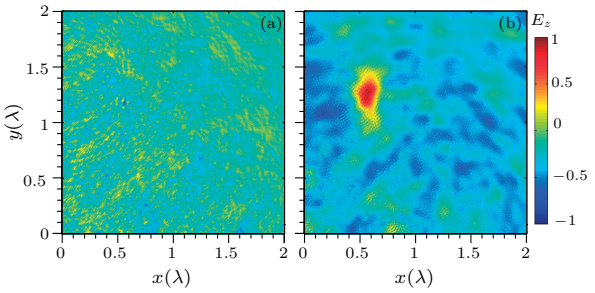


Fig. 5. Imaging results by (a) the traditional TR method and (b) the SED method in noise (SNR=−12 dB).

In summary, a simple and fast TR method based on SED processing and accompanied with wavelet analysis has been applied to locate a target in a cluttered environment. A key point of this method is to introduce the scalogram of electromagnetic energy density and wavelet analysis into the target refocusing. Our method is helpful for clutter reduction, and makes inversion algorithms more stable and repeatable.

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